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The New Emerging Model for the Structure of Cooling Cores in Clusters of Galaxies

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Abstract. New X-ray observations with XMM-Newton show a lack of spectral evidence for large amounts of cooling and condensing gas in the centers of galaxy clusters believed to harbour strong cooling flows. Here, we explore these diagnostics of the temperature structure of cooling cores with XMM-spectroscopy. We further find no evidence of intrinsic absorption in the center of the cooling flows of M87 and the Perseus cluster. To explain these findings we consider the heating of the core regions of clusters by jets from a central AGN. We find that the power of the AGN jets as estimated by their interaction effects with the intracluster medium in several examples is more than sufficient to heat the cooling flows. We explore which requirements such a heating model has to fulfill and find a very promising scenario of self-regulated Bondi accretion of the central black hole. In summary it is argued that most observational evidence points towards much lower mass deposition rates than previously inferred for cooling flow clusters.

1. Introduction

X-ray imaging observations have shown that the X-ray emitting, hot gas in a large fraction of all galaxy clusters reaches high enough densities in the cluster centers that the cooling time of the gas falls below the Hubble time, and gas may cool and condense in the absence of a suitable fine-tuned heating source (e.g. Silk 1976, Fabian & Nulsen 1977). From the detailed analysis of surface brightness profiles of X-ray images of clusters obtained with the *Einstein*, *EXOSAT*, and *ROSAT* observatories, the detailed, self-consistent scenario of inhomogeneous, comoving cooling flows emerged (e.g. Fabian et al. 1984, Nulsen 1986, Thomas, Fabian, & Nulsen 1987, Fabian 1994). The main assumptions on which the cooling flow model is based and some important implications are: (i) Each radial zone in the cooling flow region comprises different plasma phases covering a wide range of temperatures. The consequence of this temperature distribution is that gas will cool to low temperature and condense over a wide range of radii. (ii) The gas features an inflow in which all phases with different temperature

move with the same flow speed. (iii) There is no energy exchange between the different phases, between material at different radii, and no heating.

Now the first analysis of high resolution X-ray spectra and imaging spectroscopy obtained with *XMM-Newton* has shown to our surprise that the spectra show no signatures of cooler phases of the cooling flow gas below an intermediate temperature which constitutes a problem for the interpretation of the results in the conventional cooling flow picture (e.g. Peterson et al. 2001, Tamura et al. 2001). Another result is that the spectroscopic data are better explained with local isothermality in the cooling flow region (e.g. Böhringer et al. 2001a, Matsushita et al. 2001, Molendi & Pizzolato 2001) also in conflict with the inhomogeneous cooling flow model. Here, we discuss these new spectroscopic results and their implications and point out the way to a new possible model for this phenomenon. The results are mostly based on the detailed observations of the M87 X-ray halo. A detailed description of this study is provided by Böhringer et al. (2001b).

2. Spectroscopic Diagnostics of Cluster Cooling Cores

XMM Reflection Grating Spectrometer (RGS) observations of several cooling core regions show signatures of different temperature phases ranging approximately from the hot virial temperature of the cluster to a lower limiting temperature, T_{low} . Clearly observable spectroscopic features of even lower temperature gas expected for a cooling flow model are not observed. A1835 with a bulk temperature of about 8.3 keV has T_{low} around 2.7 keV (Peterson et al. 2001) and similar results have been derived for A1795 (Tamura et al. 2001). These results are very well confirmed by XMM observations with the energy sensitive imaging devices, EPN and EMOS, providing spectral information across the entire cooling core region, yielding the result that (for M87, A1795, and A1835) single temperature models provide a better representation of the data than cooling flow models (Böhringer et al. 2001a, Molendi & Pizzolato 2001) also implying the lack of low temperature components. The very detailed analysis of M87 by Matsushita et al. (2001 and the contribution to this workshop) has shown that the temperature structure is well described locally by a single temperature over most of the cooling core region, except for the regions of the radio lobes and the very center ($r \leq 1$ arcmin, ~ 5 kpc).

Among the spectroscopic signatures which are sensitive to the plasma temperature in the relevant temperature range, the complex of iron L-shell lines is most important. Fig. 1 shows simulated X-ray spectra as predicted for the XMM EPN instrument in the spectral region around the Fe L-shell lines for a single-temperature plasma at various temperatures from 0.4 to 2.0 keV and 0.7 solar metallicity. There is a very obvious shift in the location of the peak making this feature an excellent thermometer.

For a cooling flow with a broad range of temperatures one expects a composite of several of the relatively narrow line blend features, resulting in a quite broad peak. Fig. 2a shows for example the deprojected spectrum of the M87 halo plasma for the radial range 1 - 2 arcmin (outside the inner radio lobes) and a fit of a cooling flow model with a mass deposition rate slightly less than $1 M_{\odot} \text{ yr}^{-1}$ as expected for this radial range from the analysis of the surface brightness

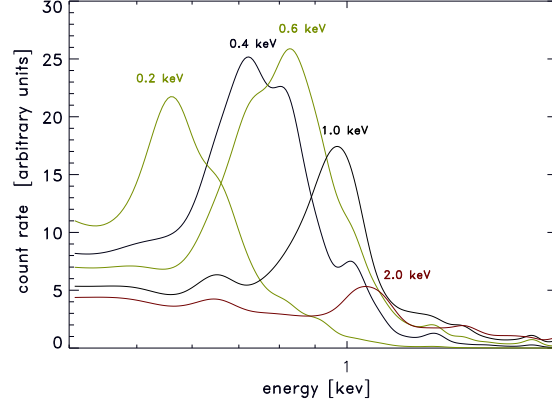


Figure 1. The Fe L-line complex in X-ray spectra as a function of the plasma temperature for a metallicity value of 0.7 solar. The simulations show the appearance of the spectra as seen with the XMM EPN. The emission measure was kept fixed when the temperature was varied.

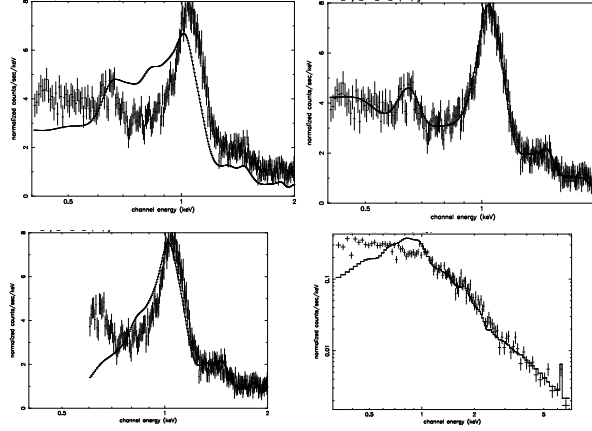


Figure 2. **(a - upper left):** XMM EPN-spectrum of the central region of the M87 X-ray halo in the radial range $R = 1 - 2$ arcmin. The spectrum has been fitted with a cooling flow model with a best fitting mass deposition rate of $0.96 M_{\odot} \text{ yr}^{-1}$ and a fixed absorption column density of $1.8 \cdot 10^{20} \text{ cm}^{-2}$, the galactic value, and a parameter for T_{low} of 0.01 keV. **(b - upper right):** same spectrum fitted by a cooling flow spectrum artificially constraint to emission from the narrow temperature interval 1.44 - 2.0 keV, where T_{low} was treated as a free fitting parameter. **(c - lower left):** same spectrum fitted with a free parameter for the internal excess absorption. The spectrum was constraint to the energy interval 0.6 to 2.0 keV. **(d - lower right):** XMM EPN spectrum of A1795 fitted with a cooling flow model with the galactic value for absorption.

profile (e.g. Stewart et al. 1984, Matsushita et al. 2001). It is evident that the peak in the cooling flow model is much broader than the observed spectral feature. For comparison Fig. 2b shows the same spectrum fitted by a cooling flow model where a temperature of 2 keV was chosen for the maximum temperature and a suitable lower temperature cut-off (1.44 keV) was determined by the fit. The very narrow temperature interval (almost isothermality) is well consistent with the narrow peak. A similar result is obtained for other clusters, e.g. A1795 as shown in Fig. 2d.

Since this diagnostics of the temperature structure is essentially based on the observation of metal lines, an inhomogeneous distribution of the metal abundances in the cluster ICM and a resulting suppression of line emission at low temperatures was suggested as a possible way to reconcile the above findings with the standard cooling flow model by Fabian et al. (2001a and contribution in these proceedings). As shown by Böhringer et al. (2001b) such a scenario will still result in a relatively broad Fe L-line feature and does not solve the problem in this case of M87.

3. Internal absorption

Another possible attempt to obtain consistency is to allow the absorption parameter in the fit to adjust freely. This is demonstrated in Fig. 2c with the same observed spectrum where the best fitting absorption column density is selected in such a way by the fit that the absorption edge limits the extent of the Fe-L line feature towards lower energies. This is actually the general finding with ASCA observations which has shown two possible options for the interpretation of the spectra of cluster core regions: (1) an interpretation of the results in form of an inhomogeneous cooling flow model which than necessarily includes an internal absorption component (e.g. Allen 2000, Allen et al. 2001), or (2) an explanation of the spectra in terms of a two-temperature component model (e.g. Ikebe et al. 1997, 1999, Makishima 2001) where the hot component is roughly equivalent to the hot bulk temperature of the clusters and the cool component corresponds approximately to T_{low} . Thus for the cooling flow interpretation to work and to produce a sharp Fe-L line feature as observed, the absorption edge has to appear at the right energy and therefore values for the absorption column of typically around $3 \cdot 10^{21} \text{ cm}^{-2}$ are needed (e.g. Allen 2000 and Allen et al. 2001 who find values in the range $1.5 - 5 \cdot 10^{21} \text{ cm}^{-2}$).

It is therefore important to perform an independent test on the presence of absorbing material in the cluster cores. Thanks to *CHANDRA* and *XMM-Newton* we can now use central cluster AGN as independent light sources for probing. Using the nucleus and jet of M87 (with *XMM*, see Fig. 3) and the nucleus of NGC1275 (with *CHANDRA*) we find no signature of internal absorption. Thus at least for these two cases it is difficult to argue for internal absorption to obtain consistency of the observations with the cooling flow model.

4. Heating Model

In view of these difficulties of interpreting the observations with the standard cooling flow model, we may consider the possibility that the cooling and mass

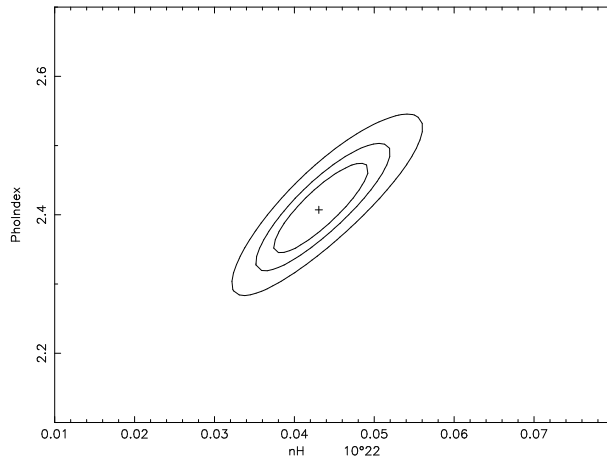


Figure 3. Constraints on the shape of the *XMM EPN*-spectrum of the nucleus of M87. The lines show the 1, 2, and 3σ confidence intervals for the combined fit of the slope (photon index) of the power law spectrum and the value for the absorbing column density, n_H , in units of 10^{22} cm^{-2} .

deposition rates are much smaller than previously thought, that is reduced by at least one order of magnitude. To decrease the mass condensation under energy conservation some form of heating is clearly necessary. Three forms of heat input into the cooling flow region have been discussed: (i) heating by the energy output of the central AGN (e.g. Pedlar et al. 1990, Binney & Tabor 1993, McNamara et al. 2000,

(ii) heating by heat conduction from the hotter gas outside the cooling flow (e.g. Tucker & Rosner 1983, Bertschinger & Meiksin 1986), and (iii) heating by magnetic fields, basically through some form of reconnection (e.g. Soker & Sarazin 1990, Makishima et al. 2001). The latter two processes depend on poorly known plasma physical conditions and are thus more speculative. The energy output of the central AGN, however, can be determined as shown below.

A heating scenario can only successfully explain the observations if among others the two most important requirements are met: (i) The energy input has to provide sufficient heating to balance the cooling flow losses, that is about 10^{60} to 10^{61} erg in 10 Gyr or on average about $3 \cdot 10^{43} - 3 \cdot 10^{44} \text{ erg s}^{-1}$, and (ii) The energy input has to be fine-tuned. Too much heating would result in an outflow from the central region and the central regions would be less dense than observed. Too little heat will not reduce the cooling flow by a large factor. Therefore the heating process has to be self-regulated: mass deposition triggers the heating process and the heating process reduces the mass deposition.

Further constraints are discussed by Böhringer et al. (2001b). The total energy input into the ICM by the relativistic jets of the central AGN can be estimated by the interaction effect of the jets with the ICM by means of the scenario described in Churazov et al. (2000). It relies on a comparison of the inflation and buoyant rise time of the bubbles of relativistic plasma which are observed e.g. in the case of NGC 1275 (Böhringer et al. 1993, Fabian et al.

Table 1. Estimated energy output from the central AGN in M87, NGC1275, and the central galaxy of the Hydra A cluster. The input parameters are the bubble radius, r_B , the ambient pressure, P_{th} , and the Keplerian velocity at the bubble location, v_K .

system	r_B	P_{th}	v_K	L_{kin}
M87	8kpc	$10^{-10} \text{ erg cm}^{-3}$	460 km s $^{-1}$	$1.2 \cdot 10^{44} \text{ erg s}^{-1}$
NGC1275	15kpc	$2 \cdot 10^{-10} \text{ erg cm}^{-3}$	600 km s $^{-1}$	$1 \cdot 10^{45} \text{ erg s}^{-1}$
Hydra A	15kpc	$2.8 \cdot 10^{-10} \text{ erg cm}^{-3}$	550 km s $^{-1}$	$2 \cdot 10^{45} \text{ erg s}^{-1}$

2001b) and requires as observational input parameters the bubble size, r_B , the ambient pressure, P_{th} , and the Keplerian velocity at the bubble radius in the cluster, v_K . The parameters and the estimated total energy output is given in Table 1 for three examples, M87, Perseus, and Hydra A. These values for the energy input have to be compared with the energy loss in the cooling flow, which is of the order of $10^{43} \text{ erg s}^{-1}$ for M87 and about $10^{44} \text{ erg s}^{-1}$ for Perseus. Thus in these cases the energy input is larger than the radiation losses in the cooling flow for at least about the last 10^8 yr . We have, however, evidence that this energy input continued for a longer time with evidence given by the outer radio halo around M87 with an outer radius of 35 - 40 kpc (e.g. Kassim et al. 1993, Rottmann et al. 1996). Owen et al. (2000) give a detailed physical account of the halo and model the energy input into it. They estimate the total current energy content in the halo in form of relativistic plasma to $3 \cdot 10^{59} \text{ erg}$ and the power input for a lifetime of about 10^8 years , which is also close to the lifetime of the synchrotron emitting electrons, to the order of $10^{44} \text{ erg s}^{-1}$, consistent with our estimate. The very characteristic sharp outer boundary of the outer radio halo of M87, noted by Owen et al. (2000), has the important implications, that this could not have been produced by magnetic field advection in a cooling flow.

Thus, we find a radio structure providing evidence for a power input from the central AGN into the halo region of the order of about ten times the radiative energy loss rate over at least about 10^8 years (for this representative example of M87). The energy input could therefore balance the heating for at least about 10^9 years . The observation of active AGN in the centers of cooling flows is a very common phenomenon. E.g. Ball et al. (1993) find in a systematic VLA study of the radio properties of cD galaxies in cluster centers, that 71% of the cooling flow clusters have radio loud cDs compared to 23% of the non-cooling flow cluster cDs. Therefore we can safely assume that the current episode of activity was not the only one in the life of M87 and its cooling flow.

The mechanism for a fine-tuned heating of the cooling flow region should most probably be searched for in a feeding mechanism of the AGN by the cooling flow gas. The most simple physical situation would be given if simple Bondi type of accretion from the inner cooling core region would roughly provide the order of magnitude of the power output that is observed and required. Using the classical formula for spherical accretion from a hot gas by Bondi (1952) we can

obtain a very rough estimate for this number. For the proton density near the M87 nucleus ($r \leq 15$ arcsec) of about 0.1 cm^{-3} , a temperature of about 10^7 K (e.g. Matsushita et al. 2001), and a black hole mass of $3 \cdot 10^9 M_\odot$ (e.g. Ford et al. 1994) we find a mass accretion rate of about $0.01 M_\odot \text{ yr}^{-1}$ and an energy output of about $7 \cdot 10^{43} \text{ erg s}^{-1}$, where we have assumed the canonical value of 0.1 for the ratio of the rest mass accretion rate to the energy output. The corresponding accretion radius is about 50 pc (~ 0.6 arcsec). This accretion rate is more than a factor of 1000 below the Eddington value and thus no reduction effects of the spherical accretion rate by radiation pressure has to be expected. Small changes in the temperature and density structure in the inner cooling core region will directly have an effect on the accretion rate. Therefore we have all the best prospects for building a successful self-regulated AGN-feeding and cooling flow-heating model.

5. Conclusions

Several observational constraints have let us to the conclusion that the mass deposition rates in galaxy cluster cooling cores are not as high as previously predicted. The new X-ray spectroscopic observations with a lack of spectral signatures for the coolest gas phases expected for cooling flows and the lower mass deposition rates indicated at other wavelength bands than X-rays are more consistent with mass deposition rates reduced by one or two orders of magnitude below the previously derived values. This can, however, only be achieved if the gas in the cooling flow region is heated. The most promising heating model is a self-regulated heating model powered by the large energy output of the central AGN in most cooling flows.

Most of the guidance and the support of the heating model proposed here (based on concepts developed in Churazov et al. 2000, 2001) is taken from the detailed observations of a cooling core region in the halo of M87 and to a smaller part from the observations in the Perseus cluster. These observations show that the central AGN produces sufficient heat for the energy balance of the cooling flow, that the most fundamental and classical accretion process originally proposed by Bondi (1952) provides an elegant way of devising a self-regulated model of AGN heating of the cooling flow, and that most of the further requirements that have to be met by a heating model to be consistent with the observations can most probably be fulfilled. Since these ideas are mostly developed to match the conditions in M87, it is important to extent such detailed studies to most other nearby cooling flow clusters.

In this new perspective the cooling cores of galaxy clusters become the sites where most of the energy output of the central cluster AGN is finally dissipated. Strong cooling flows should therefore be the locations of AGN with the largest mass accretion rates. While in the case of M87 with a possible current mass accretion rate of about $0.01 M_\odot \text{ y}^{-1}$ the mass addition to the black hole (with an estimated mass of about $3 \cdot 10^9 M_\odot$) is a smaller fraction of the total mass, the mass build-up may become very important for the formation of massive black holes in the most massive cooling flows, where mass accretion rates above $0.1 M_\odot \text{ y}^{-1}$ become important over cosmological times.

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